Mathematical Modelling of Automedium Cyclones

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Foreword

Since 1976, numerous projects have been initiated in Alberta by industry and by academic research institutions which are aimed at better utilization of Alberta's energy resources.

These research, development and demonstration efforts were funded by the Alberta/Canada Energy Resources Research Fund (A/CERRF), which was established as a result of the 1974 agreement on oil prices between the federal government and the producing provinces.

Responsibility for applying and administering the fund rests with the A/CERRF Committee, made up of senior Alberta and federal government officials.

A/CERRF program priorities have focused on coal and conventional energy resources, as well as energy conservation and renewable energy. Program administration is provided by staff within the Scientific and Engineering Services and Research Division of Alberta Energy.

In recognition of the importance of coal to Alberta's economy, the Alberta Office of Coal Research and Technology was established in 1984 within Alberta Energy and Natural Resources (now Alberta Energy). Its primary purpose is to encourage the development and application of new technologies related to Alberta coals. The Office provides funding contributions to research and development projects in industry, academic institutions and otner research establishments and monitors their progress in an overall program of improving the production, transportation and marketability of Alberta coals.

In order to make research results available to industry and others who can use the information, highlights of studies are reported in a series of technology transfer booklets. For more information about other publications in the series, please refer to page 10.

Mathematical Modelling of Automedium Cyclones

In today's highly competitive coal marketplace, producers would like to sell all the coal they can mine but, at the same time, customer requirements dictate that coal should not contain more than a minimum amount of inert, non-combustible material. This means that coal must be cleaned to reduce the amount of inert substances (expressed as ash content) to acceptable levels. Since the 1970s, cleaning processes for western Canadian metallurgical coals have included devices known as automedium cyclones, or AMCs. These devices, which are also known as compound water cyclones or water-only cyclones, are needed to recover fine particles that average 30 to 35 per cent by weight of coking coals.

Experience has shown that the ash content of coals cleaned by automedium cyclones varies widely. However, attempts by operators to optimize AMC performance by making manual adjustments have had only limited success. The situation is further hampered by a lack of monitoring instruments and control strategies to deal effectively with process changes.

Therefore, it was believed a better understanding of the coal separation mechanisms that occur within AMCs would be beneficial. This was especially so if it led to the development of mathematical models that would relate AMC performance to process changes and could be used as the basis for process control measures. This might allow process operators to produce coal having more uniform properties.

With these goals in mind, in 1984/85 the Alberta Office of Coal Research and Technology administered an investigation of cyclones at the University of Alberta, Department of Mineral Engineering. It was performed under the direction of Dr. L.R. Plitt and through the auspices of the university's Hydrocarbon Research Centre Inc. Funding was provided by the Alberta/Canada Energy Resources Research Fund (A/CERRF).

Background

Historically, cyclone separators have been popular in many industrial applications because of their relatively low cost and versatility in performing liquid-liquid, solid-liquid and solid-solid separations. Although cyclones are geometrically and operationally simple, separation mechanisms associated with them are both complex and not well understood.

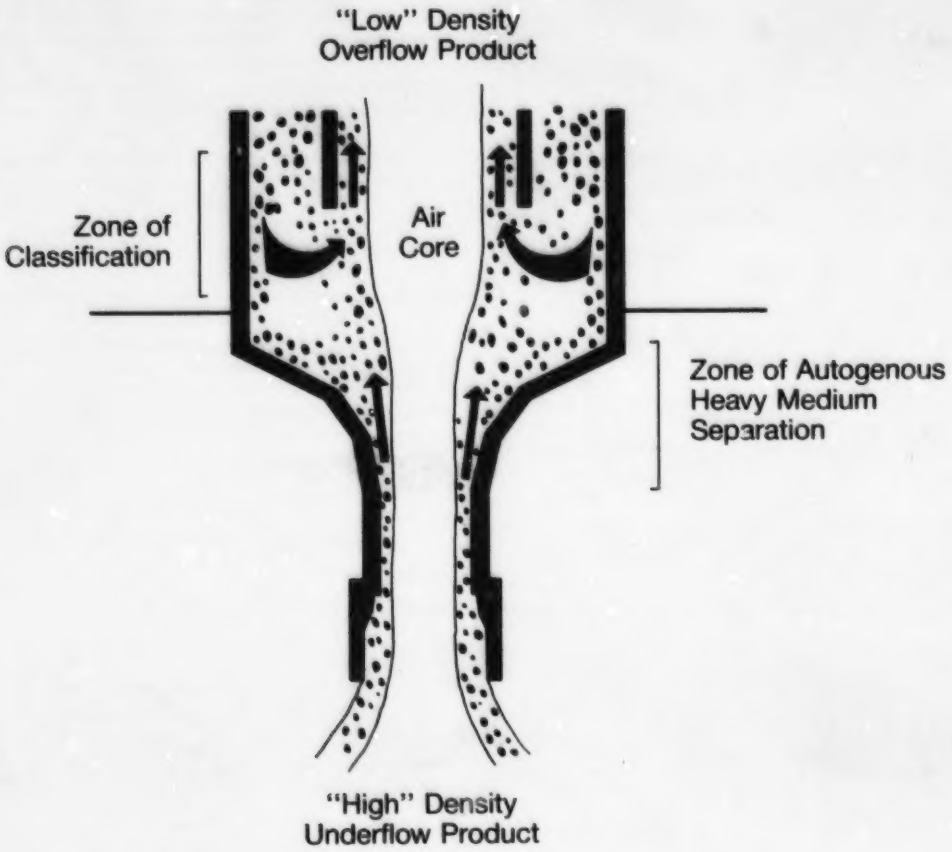
When slurries of solid substances are fed into hydronic cyclones (so called because they are used to separate solid substances from water slurries), individual particles are subjected to centrifugal forces caused by rotational fluid motion. If they were the only forces at work inside a cyclone, settling behaviour could be explained by the size and density distribution of individual particles as they migrate toward the outer wall of the cyclone.

Working against centrifugal forces is a countercurrent movement of water toward the centre of the cyclone. This causes mechanical entrainment of particles whose "slip velocity" is too low to allow them to move toward the wall.

In the case of homogeneous mineral ores, these competing forces cause fine particles to be swept away with water in the cyclone's overflow (near the top of the unit if it is operated in an upright position), while coarser particles end up as a high density product that is diverted out the opposite end in the underflow. Furthermore, fluid motion inside the cyclone creates air movement from the underflow end toward the overflow end.

Attempts to use mathematical equations to predict the distribution of particle sizes in the underflow and overflow streams from cyclones have shown that allowance must be made for yet another phenomenon. It is necessary to assume that some portion of the feed solids is short-circuited to the underflow, while the remainder of the feed undergoes separation on the basis of particle-settling characteristics.

Generalized Separation Mechanisms in an Automedium Cyclone



(Source: *Mathematical Modelling of Automedium Cyclones*, Turak, A.A., MSc Thesis, University of Alberta, 1985)

Because the origins of this bypass mechanism are not well understood, existing mathematical models – including those that have been modified to account for bypass – are of limited value in predicting the behaviour of heterogeneous materials, like coal, in cyclones. Before the separation characteristics of coal can be modelled with a reasonable degree of accuracy, however, the bypass mechanism must be better understood.

From previous attempts to understand the bypass mechanism, it appeared that lower density components were less likely than higher density particles to go to the bypass stream. This was thought to be due to "autogenous heavy medium separation effects" which occur when heavier particles move toward the apex valve at the underflow end of the cyclone. At this point, less dense particles are stripped from the downward moving underflow stream by rising fluid. Below certain particle sizes, specific gravity effects become negligible.

This separation effect is exploited in modified versions of cyclones, the AMCs, which are believed to operate somewhat differently from conventional classifying cyclones. In an AMC, particles that do not report to the overflow find their way down to form a rotating bed at the bottom of the cyclone. Here, they are stratified according to size and density, with the upper layers of the bed undergoing erosion by the rotating fluid of the vortex. Stratification in the bed and the extent of penetration of the erosion

effect determine the amount and characteristics of the material separated from the stream, which gradually works its way to the apex.

The conceptual model evolving from this description has three separation zones and a bypass flow, each of which can be described by mathematical equations that account for the fraction of each size and density class of particles that are routed to the underflow.

Study Approach

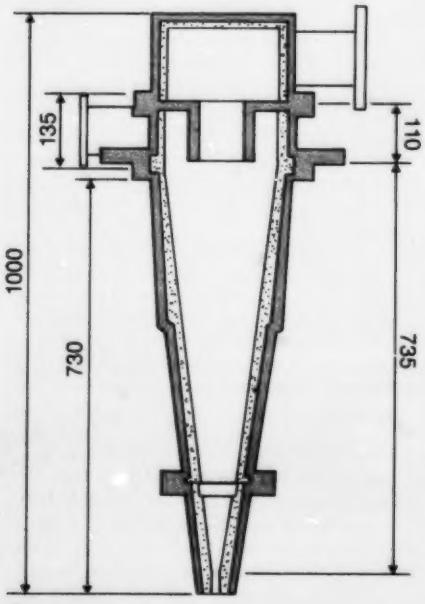
The researchers decided that the simplest way to model AMC behaviour was to use the device to separate silica, a homogeneous solid.

A closed-loop cyclone pilot plant was built at the University of Alberta to separate slurries of silica. After a steady state was reached during a series of six tests, the overflow and underflow product streams were sampled. Samples were weighed, filtered, dried and analysed for particle size.

It was found that a stable bed had formed in the AMC, but none of the existing mathematical models correctly predicted the similarity between particle size in the bed and underflow stream. However, on the basis of this work and some related experimental results reported in the literature, a tentative model was proposed for metallurgical coals. This is a generalized form of the well-established empirical model used for classifying cyclones.

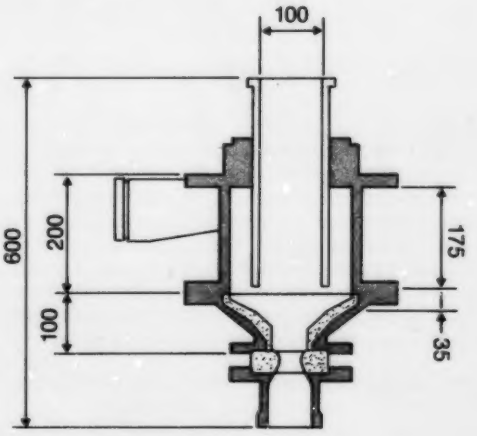
A coal-sampling program was undertaken at the Fording River coal mine in Elkford, B.C. High frequency sampling (three samples per hour) of metallurgical coal streams from an AMC revealed that solids concentration and ash content varied widely during typical operation of a commercial-scale coal-washing operation, thus demonstrating the importance of improving control over the separation process. A large sample of Fording's coal was returned to the university laboratory where 48 pilot plant tests were conducted.

Comparison of a Classifying and an Automedium Cyclone



Typical 20 cm (8 in.)
Classifying Cyclone

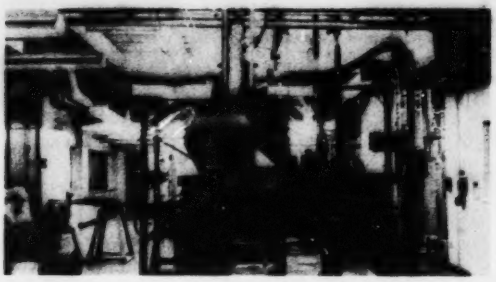
All dimensions
in millimetres



Typical 20 cm (8 in.)
Automedium Cyclone

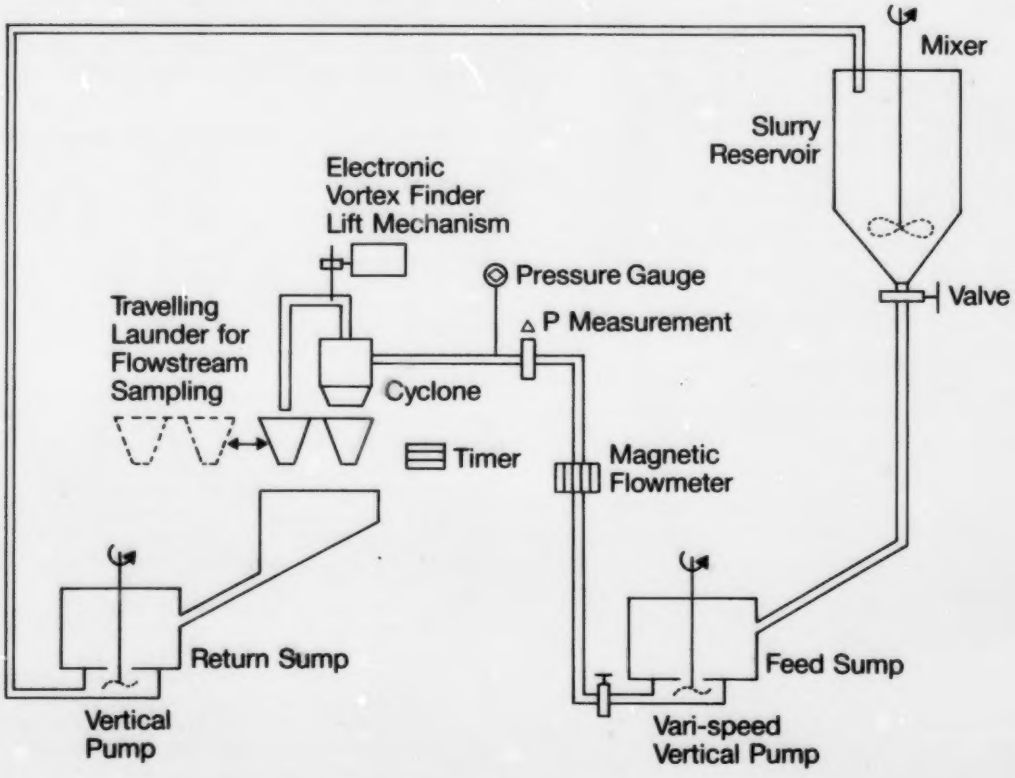
(Source: *Mathematical Modelling of Automedium Cyclones*, Turak, A.A., MSc Thesis, University of Alberta, 1985)

Using the same pilot-plant arrangement employed during the silica-testing program, experiments were designed to study systematically five operational factors. They were: (1) feed solids concentration; (2) vortex finder diameter; (3) apex diameter; (4) volumetric flow rate; and (5) vortex finder clearance (an adjustable mechanism within the cyclone). For each test, samples of the underflow and overflow product streams were analysed for particle size, and the specific gravity of each size fraction was determined. From these data, a family of partition curves was constructed as a function of particle size (one curve for each specific gravity fraction).



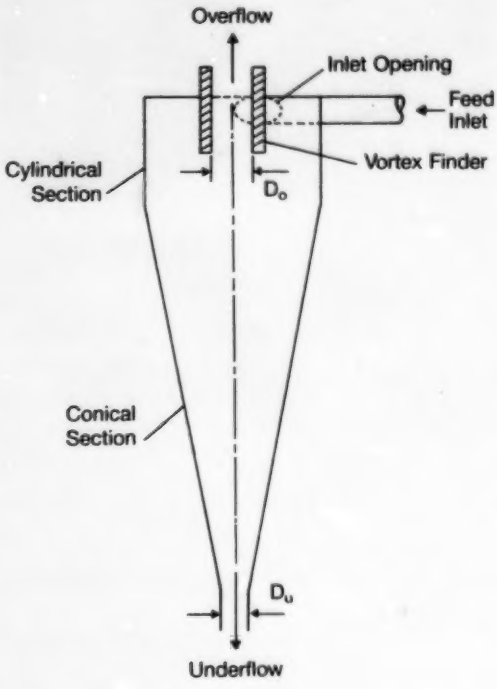
The closed-loop cyclone pilot plant.

Schematic of Closed-Loop Cyclone Pilot Plant



(Source: *Mathematical Modelling of Autogenous Cyclones*, Turak, A.A., MSc Thesis, University of Alberta, 1985)

Principal Dimensional Variables in a Cyclone Classifier



(Source: *Mathematical Modelling of Automedium Cyclones*, Turak, A.A., MSc Thesis, University of Alberta, 1985)

Results

The researchers noted that the bed formed during coal separation differed from experiments involving silica. Whereas the particle size distribution of silica was similar in the bed and underflow, in the case of coal, the bed consisted of coarser and lighter material than in the underflow.

It was postulated that a percolation mechanism was responsible for particle stratification in the bed. This was followed by erosion caused by the upward movement of air. A subsequent series of laboratory tests confirmed that percolation – whereby fine particles drift downward through the interstitial spaces between coarse particles – occurs in non-stationary beds when there is no net upward flow of air. When an airstream is added, coarser particles, rather than fines, would be transported. This is the opposite of what might be expected in the absence of a percolation mechanism. This means that fines blanketed by the coarse particles would go to the underflow stream.

For each of the 48 pilot plant tests, six density fractions were collected, resulting in the generation of 288 partition curves which were used as the basis for data interpretation. In analysing the data, it was discovered that existing numerical techniques were inadequate for determining the values of seven partition curve parameters embodied in the equations for each separation zone. Therefore, an interactive graphics program called CPLOT was developed for this project.

Consequently, predictive equations were produced and used to generate simulated partition data. When these numbers were plotted against measured partition data, it was apparent that for the cyclone operation range investigated in this study, the mathematical model was capable of accurately predicting the particle size distribution of cleaned metallurgical coal from Fording's mine.

Although researchers believe the model is too complex in its present form and further experiments are needed to simplify it, they claim that operators and equipment designers can use it now to obtain a semi-quantitative understanding of AMC operation. They contend that the use of partition curves allows the model to be used for any other metallurgical coal from the mountain region.

Predictive Equations Used in Mathematical Model of Automedium Cyclones

$$d_{50A} = 678.7 \left(\frac{D_u}{D_o}\right)^{2.36} h^{0.66} (\rho_s - \rho)^{1.14}$$

$$d_{50B} = \frac{28.1\ D_o^{0.72}}{(\rho_s - \rho)^{0.24}}$$

$$d_{50C} = \frac{1.06\ D_o^{2.38}}{h^{0.23} (\rho_s - \rho)^{0.945}}$$

$$m_A = 0.91 \left(\frac{D_u}{D_o}\right)^{0.41} h^{0.14}$$

$$m_B = \frac{0.08\ h^{0.24}\ Q^{0.52}}{D_o\ D_u^{0.31}} \frac{\rho_s^{2.54}}{(\rho_s - \rho)^{0.76}}$$

$$m_C = \frac{0.93\ h^{0.15}}{D_o^{0.39}\ D_u^{0.34}} \frac{\rho_s^{3.20}}{(\rho_s - \rho)^{1.24}}$$

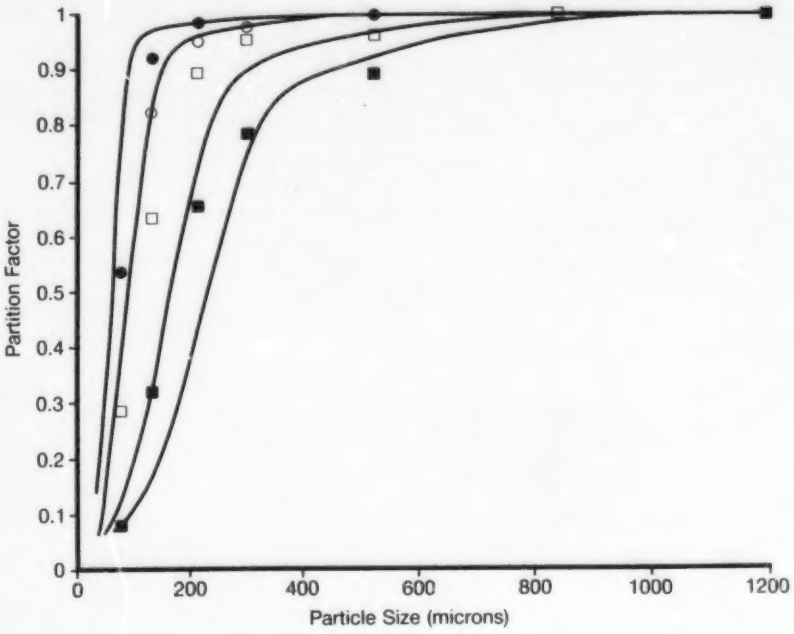
$$R = \frac{0.36}{D_o^{3.71}} \frac{\rho_s^{7.69}}{(\rho_s - \rho)^{3.14}}$$

Nomenclature

A	:	Zone of bed partitioning in cyclone
B	:	Secondary classification zone in cyclone
C	:	Primary classification zone in cyclone
D_o	:	Overflow orifice diameter [cm]
D_u	:	Underflow orifice diameter [cm]
P	:	Partition function; fraction of a specific feed component reporting to the underflow
Q	:	Volumetric flow rate [L/min]
R	:	Bypass flow in the cyclone
X	:	Material lifted from bed for reclassification
Y	:	Particle size based partition function
a	:	Partitioning in zone A
b	:	Partitioning in zone B
c	:	Partitioning in zone C
d	:	Particle diameter [μm]
d_{50}	:	Size of separation; corrected size of particle, 50% of which reports to the underflow [μm]
d_{50A}	:	Size of separation in zone A [μm]
d_{50B}	:	Size of separation in zone B [μm]
d_{50C}	:	Size of separation in zone C [μm]
h	:	Vortex finder clearance, distance from bottom of vortex finder to conical bottom directly beneath the vortex finder [cm]
m	:	Sharpness of separation in the classifier model
m_A	:	Sharpness of separation in zone A
m_B	:	Sharpness of separation in zone B
m_C	:	Sharpness of separation in zone C
ρ	:	Density of fluid [g/ml]
ρ_s	:	Density of particle [g/ml]

(Source: *A Generalized Model for Classifying and Automedium Cyclones*, Turak, A.A., L.R. Plitt and B.C. Flintoff, 3rd International Conference on Hydrocyclones, Oxford, England, Sept. 30 - Oct. 2, 1987)

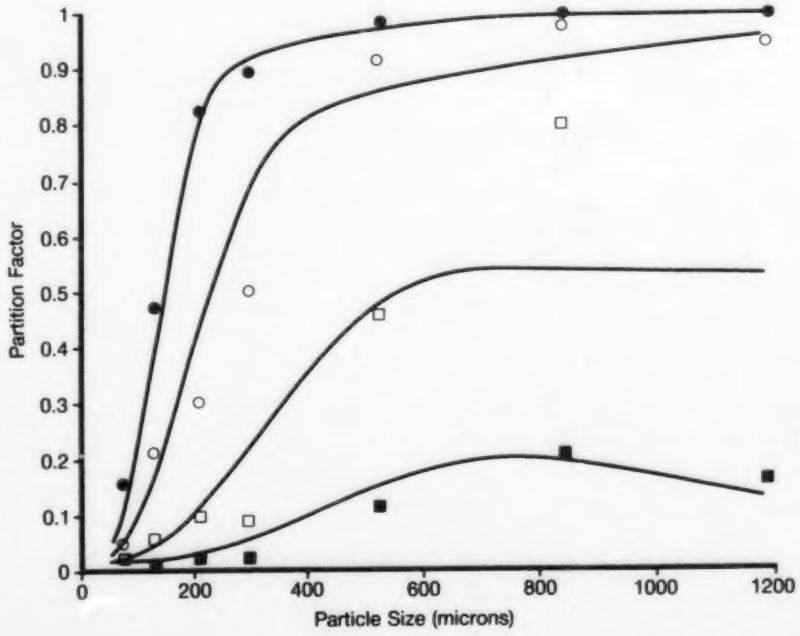
Partitioning Data and Model Prediction



Mean Specific Gravity of Solids
- ● 2.20
- ○ 1.80
- □ 1.45
- ■ 1.33

Model

Test Conditions
D_o = 7.19 cm
D_u = 5.08 cm
h = 7.11 cm
Q = 473 L/min



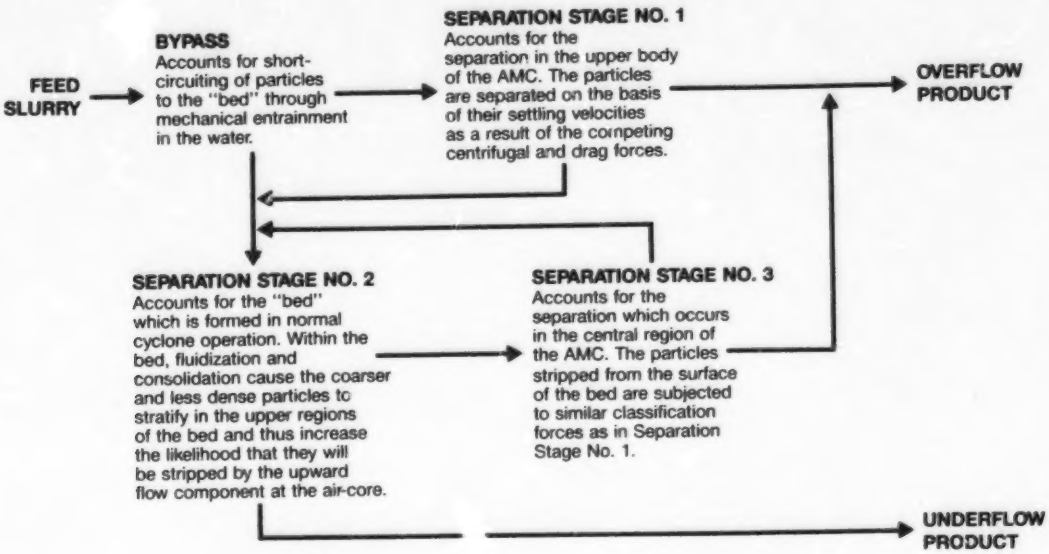
Mean Specific Gravity of Solids
- ● 2.20
- ○ 1.80
- □ 1.45
- ■ 1.30

Model

Test Conditions
D_o = 10.16 cm
D_u = 5.08 cm
h = 7.11 cm
Q = 473 L/min

(Source: *A Generalized Model for Classifying and Automedium Cyclones*, Turak, A.A., L.R. Plitt and B.C. Flintoff, 3rd International Conference on Hydrocyclones, Oxford, England, Sept. 30 - Oct. 2, 1987)

A Conceptual Model of Particle Separation in an Automedium Cyclone


FEED SLURRY
BYPASS
Accounts for short-circuiting of particles to the "bed" through mechanical entrainment in the water.
SEPARATION STAGE NO. 1
Accounts for the separation in the upper body of the AMC. The particles are separated on the basis of their settling velocities as a result of the competing centrifugal and drag forces.
OVERFLOW PRODUCT
SEPARATION STAGE NO. 2
Accounts for the "bed" which is formed in normal cyclone operation. Within the bed, fluidization and consolidation cause the coarser and less dense particles to stratify in the upper regions of the bed and thus increase the likelihood that they will be stripped by the upward flow component at the air-core.
SEPARATION STAGE NO. 3
Accounts for the separation which occurs in the central region of the AMC. The particles stripped from the surface of the bed are subjected to similar classification forces as in Separation Stage No. 1.
UNDERFLOW PRODUCT

(Source: *Mathematical Modelling of Automedium Cyclones: Executive Summary of Final Report to Hydrocarbon Research Centre Inc.*, Plitt, L.R. and B.C. Fintoff, University of Alberta, July 1985)

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